Solenoid Quench Heater

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The goal of this study was to understand how efficient quench heaters for the solenoid can be and what quench delay one can expect. The method that was used during this study is similar to one used for the quench propagation study [1].

I. Evaluation of the heater parameters

Quench heaters are usually made of stainless steel foil (t = 50 μm, w = 1 mm) arranged in a certain pattern to reach needed resistance, cover certain area of the winding, and obtain certain thermal capacity, that would allow to limit maximal temperature of the heater. The heater is usually fed by a pulsed power supply based on discharge of a capacitor through the resistance of the heaters. The capacitance of the pulser available in IB-1 can be made **2400 μF** or higher. The maximal voltage of the pulser is **400 V** and the maximal current is **200 A**. To obtain maximal power during the shortest time, the resistance of the heaters must be as low as possible. With the limitations of the power supply, we can have the total resistance of about 2 Ohm. With two identical side or barrel heaters working in parallel, the resistance of each heater must be ~4 Ohm or more at 4 K. Specific resistance of stainless steel 304 at 4K is ~ $5 \cdot 10^{-7}$ Ohm·m. So, for the 50 μm 1-mm wide foil we need the total length of ~ 0.5 m.

The total mass of the heater material is then ~ ρ*L*w*t ≈ 0.2 g or 0.025 cm^3. The energy required to bring the temperature of this mass to the level of about 300 K can be found if we know enthalpy of this material at different temperatures. A satisfactory approximation of the heat capacity of stainless steel 304 (J/m^{3}K) and its enthalpy (J/m^3) as a function of temperature is shown in Fig 1:

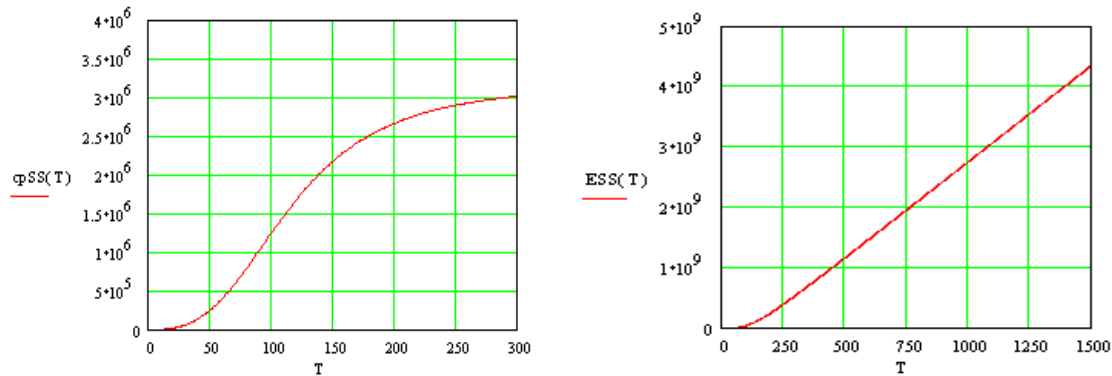Fig. 1: Specific heat and enthalpy of stainless steel 304.

Energy deposition in one pulse is W = 1/2CU^2 ≈ 200 J. At 400 V, this corresponds to ~100 J for each heater or ~4*10^9 J/m^3. The heater temperature can be found from Fig. 1: it can reach ~1500 K. So, even with the minimal capacitance of the energy storage element of the pulser, one should limit charging voltage to keep the temperature of the heater on the level below 500 K (~ 200 C), which Kapton insulation can reliably withstand. This restriction translates into the maximal voltage of the pulser of ~200 V. Fig. 2 shows the heater temperature dependence of the charging voltage.
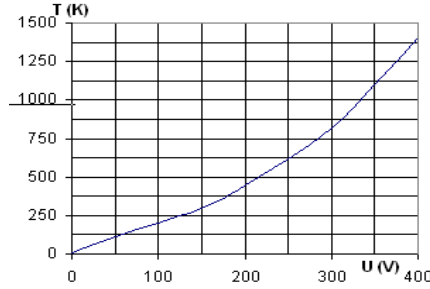
Fig. 2: Heater temperature as a function of the charging voltage (C = 2400 mkF)

II. Heat transfer from the heater to the coil

The next question is how quickly can this heat be transferred to the nearest layer of a superconductor and bring its temperature above the critical level of 9.2 K. Here the heat transfer problem was modeled using time-step modeling of foil heating, heat transfer though the layer of Kapton insulation separating the heater from the coil winding, and the temperature increase of the NbTi strand. Specific heat of NbTi was taken as it was defined during quench modeling in [1]. Thermal conductivity of the Kapton insulation depends on temperature quite weakly, so average value of ~0.04 W/m-K was accepted through all the range of the temperature change. Thickness of the Kapton insulation of 0.2 mm was accepted for this run.

Power density in the heater reaches 100 W/mm^2 at maximal current of 100 A per one heater, but decays quickly as current decays (Fig. 3).
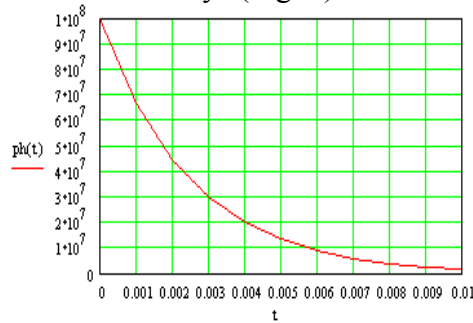

Fig. 3: Power deposition rate (W/m^2) for the heater.

Graphs showing the temperature rise in the heater and in the NbTi strand are shown in Fig. 4. Note the x10 scale for the strand temperature. On the same graph, critical temperature of NbTi is shown as a line parallel to the time axis.
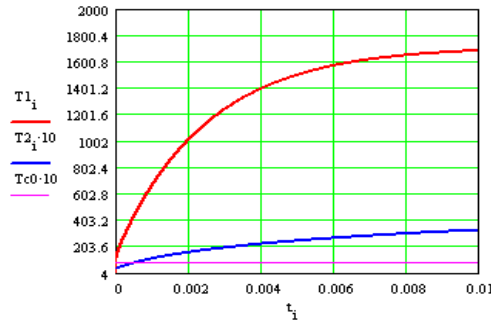

Fig. 4: Temperature diagram.

One can immediately notice very slow rate of temperature rise in the strand. Nevertheless, the strand quenches well before the current decays; this tells that the heater can help the coil to quench.

III. Optimization of heater parameters

Changing the input current, it is possible to vary power density in the heater. As a result, quench delay time will change. Corresponding graph is shown in Fig. 5. Here the power density (W/m^3) is along the horizontal axis, and the vertical axis gives quench delay in milliseconds. It is possible to notice very weak dependence of the quench start delay on the power density: one order of magnitude in the delay time is reached after power density was changes by four orders of magnitude (or current changed by two orders of magnitude).
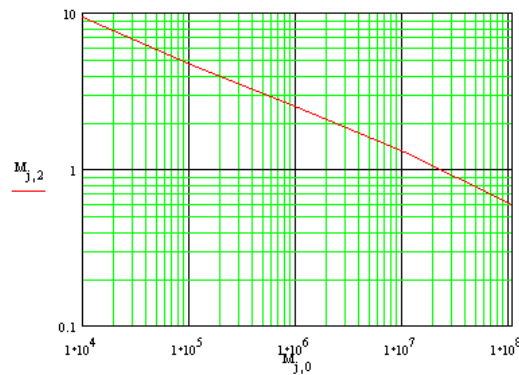

Fig. 5: Time delay (ms) as a function of the heater power density (W/m^2)

As a result of this weak dependence, pulser parameters can be chosen so that heater temperature is kept at minimal level that insures safe work of the device. The graph in Fig. 6 shows heater temperature (K) as a function of the heater maximal power density (W/m^2), which can be compared with Fig. 2.
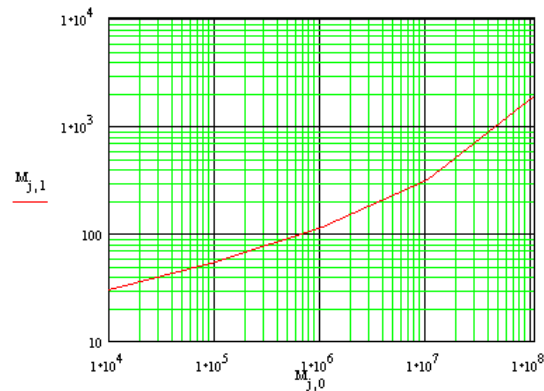

Fig. 6: Heater temperature (K) as a function of the heater power density (W/m^2)

Comparing Fig. 5 and Fig. 6 (or Fig. 2), one can tell that it would be quite safe to work in the region of p = 1*10^7 W/m^2 (I = 50 A per one heater, U = 150 V) to ensure delay time of less than 1.5 ms with the maximal heater temperature of less that 400 K.

Changing thickness of the Kapton insulation results in corresponding change in the coil quench delay time. As it is shown in Fig. 7 for $p = 10^8$ W/m^2, changing the thickness twice results in approximately twice as fast heat transfer. So, making insulation thickness equal to 100 μm (instead of 200 μm that was accepted in this note) will make the quench delay at 10^7 W/m^2 of less than 1 ms.

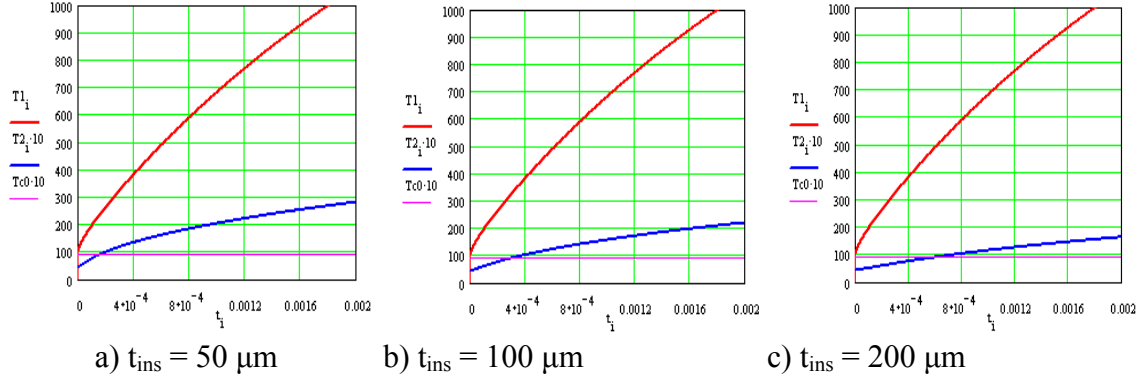| a) t_{ins} = 50 μm | b) t_{ins} = 100 μm | c) t_{ins} = 200 μm |

Fig. 7: Time delay as a function of Kapton insulation thickness

Intermediate Summary:

It was shown that it is possible to find the heater configuration and insulation thickness so that the heater can quench superconducting winding during ~ 1 ms time, that is much less than the time scale of the natural quench propagation event. So, more of coil's energy can be evacuated from the LHe zone saving time and LHe power needed for the coil subsequent cooling down.

IV. Testing the heater

Based on the results obtained during the first part of the study, several heaters were fabricated and some of them tested using the available power supply. Besides, a standard heater made by MINCO was tested.

The goal of the test was to measure strand temperature rise rate. As a temperature gauge we've chosen to use a thermocouple. At the LHe temperature, we expect to see the temperature rise of ~5 K in ~1 ms. So, the thermocouple's time constant should allow this time resolution. The Chromega-Constantan (type E) thermocouple was chosen with the wire diameter of 50 μm. Sensitivity of this thermocouple is the highest among other types: ~ 40 mV per 1000 °F or ~ 70 μV/°C. To reliably observe the expected voltage rise of ~ 0.35 mV on the screen of the available oscilloscope with the sensitivity ~ 5 mV/cm, corresponding to ~5 K temperature rise, some additional amplification of the thermocouple output signal was needed. A simple battery powered amplifier was built for this purpose with the amplification of 100. The total sensitivity f the thermocouple with the amplifier thus becomes ~ 7 mV/°C. Calibration of the amplifier showed that the sensitivity is ~ 6 mV/°C at the room temperature.

Two heaters have been tested: the home-made heater made of 50 μm foil with the resistance of ~ 8 Ohm (heater #1) and the MINCO HK5577 heater with the resistance of 4.9 Ohm (heater #2). Knowing the resistance of the heater, it was possible to evaluate the capacitance of the power supply by measuring the battery discharge time constant: C = 7500 μF. This allows calculating the stored energy used in the data tables below. To compare the data with the results of modeling, heat deposition per the unit of the heater

area was used instead of the power source charge voltage that was used during the test. Surface area for heater #1 is ~500 mm^2 and for the heater #2 it is ~250 mm^2.

   Time count starts with the moment when the power supply is activated. Delay time row of the table below shows moments when the temperature rise curve can be reliably distinguished from the ground level. The temperature rise rate row shows the rate of the thermocouple temperature increases after rise starts. Red values mean that the Kapton insulation starts melting, so these parameters must not be used.

Heater #1

U (V)	80	100	120	140	160
w (J/m^2)	4.8·10^4	7.5·10^4	1.1·10^5	1.5·10^5	2·10^5
p (W/m^2)	1.6·10^6	2.5·10^6	3.6·10^6	4.9·10^6	6.4·10^6
Delay time (ms)	30	20	20	20	20
Temp. rise rate (°C / ms)	~0.035	~0.06	~0.12	~ 0.175	~0.23

Heater #2

U (V)	60	80	100
w (J/m^2)	5.4·10^4	9.6·10^4	1.5·10^5
p (W/m^2)	2.9·10^6	5.2·10^6	8.2·10^6
Delay time (ms)	20	20	12
Temp. rise rate (°C / ms)	~0.16	~0.2	~0.175

While comparing the two tables, it is necessary to keep in mind that the insulation thickness in the first one is 0.2 mm and in the second one it is 0.05 mm. That's why we see some difference in the heat propagation rate and the delay time.
For both heaters, expected quench time is quite different from what the model shows at 4.5 K. This can be explained by the difference in the material properties at 4.5 K and the room temperature (300 K). The two tables below show results of modeling for the heater #2 expressed in the terms similar to the experimental data above.

Heater #2, T = 300 K

U (V)	40	60	80	100
w (J/m^2)	2.4·10^4	5.4·10^4	9.6·10^4	1.5·10^5
p (W/m^2)	1.3·10^6	2.9·10^6	5.2·10^6	8.2·10^6
Delay time (ms)	12	10	7	5
Temp. rise rate (°C / ms)	~0.15	~0.25	~0.33	~ 0.42

Heater #2, T = 4.5 K

U (V)	10	20	30	40	60
w (J/m^2)	1500	6000	1.3·10^4	2.4·10^4	5.4·10^4
p (W/m^2)	0.8·10^5	3.25·10^5	7.25·10^5	1.3·10^6	2.9·10^6
Temp. rise rate (°C / ms)	~3.5	~5	~7	~ 10	~20
Quench moment (ms)	1.4	1.0	0.7	0.5	0.25

   Comparing the 300 K modeling table with the 300 K data table for the heater #2, we see that the modeling gives higher temperature rise rate than it was obtained during the test, but the values are quite comparable. Switching to 4 K for the same heater results in

the dramatic increase in the temperature rise rate due to temperature dependence of the material thermal properties.

So, the test data properly reflect what the modeling show, and at 4 K we can expect the quench delay time of the order of 1 ms.

V. Quench Heater for the Test Solenoid

Based on the results of this study, the next quench heater configuration was suggested for the first test solenoid:

1. Four MINCO HK5577 heaters are placed on the coil barrel. Nominal resistance of each heater is 4.9 Ohm. Two heaters are connected in parallel to form a couple, and the two couples are connected in series to result in the total heater resistance of 4.9 Ohm.

2. We need to have relatively high voltage to achieve needed power of the heater for fast heat transfer. Simultaneously, we should lower dissipated heat to prevent the heater from being damaged by the heat. This means that the capacitance must be as low as possible. To work below the melting point of the Kapton insulation, the heaters must dissipate less than 5 J per 1 cm^2 of the active surface. With the storage capacitance C = 2.4 mF, this corresponds to the voltage U = 120 V.

3. To be able to scan through a range of the heater power, the minimal voltage should be at least 3 times lower (that will give us about an order of the magnitude of the heater power). It is comparable with the lowest voltage of ~ 40 V that you can charge the power supply with.

References:

1. I. Terechkine, P. Bauer
 Proton Driver Front End Focusing Solenoid Quench Protection Studies. Part I: Method Description and the First Iteration.
FNAL TD note TD-06-003